The Cajon Pass example has identified that the communication, electric power transmission, and fuel pipeline lifelines generally can be analyzed as a set of discrete collocation points. The restoration of service at any one point is not a strong function of the restoration work that is needed at other collocation points. Thus, if there is a restoration problem that will take a long time compared to the other locations, it becomes the "critical path" that sets the time period for the restoration of the entire lifeline system. Transportation lifeline collocation points, however, are sensitive to the damage that has occurred along the route of the transportation system. That is, often it is necessary for the heavy equipment and material needed to have access to the damage location by traveling along the highway or railroad itself. Thus, before access to a particular bridge can be made, it may be necessary to first repair all the damage sites on the route prior to that location.

4.0 ANALYSIS METHOD

In performing an analysis of the impacts of collocation or close proximity on lifeline systems and components for earthquake or other at-risk conditions, it is important that the most accurate data and analyses be used to characterize the response of the individual lifelines to the loads applied. Whatever method is applied must be applicable to all the components within the lifeline system, because the evaluation of the collocation impacts requires comparing the calculated time to restore the lifeline to its intended service for both the collocation and an assumed non-collocation condition. The general methods for performing such an analysis are shown in the flow chart of Figure 1. If owner-supplied or site specific analysis methods are not available for use in the detailed calculations, the following material (Sections 4.1, 4.2, 4.3, and 4.4) can be used as the alternative analysis method. This is discussed more fully in the following material.

Figure 1 shows a four step approach that can be used to analyze any lifeline under at-risk conditions (e.g., an natural or manmade disaster condition). However, the present study only develops the detailed information needed to analyze earthquake conditions. The steps are:

   1) Data Acquisition;
   2) Calculation of Lifeline Vulnerability;
   3) Collocation Analysis; and
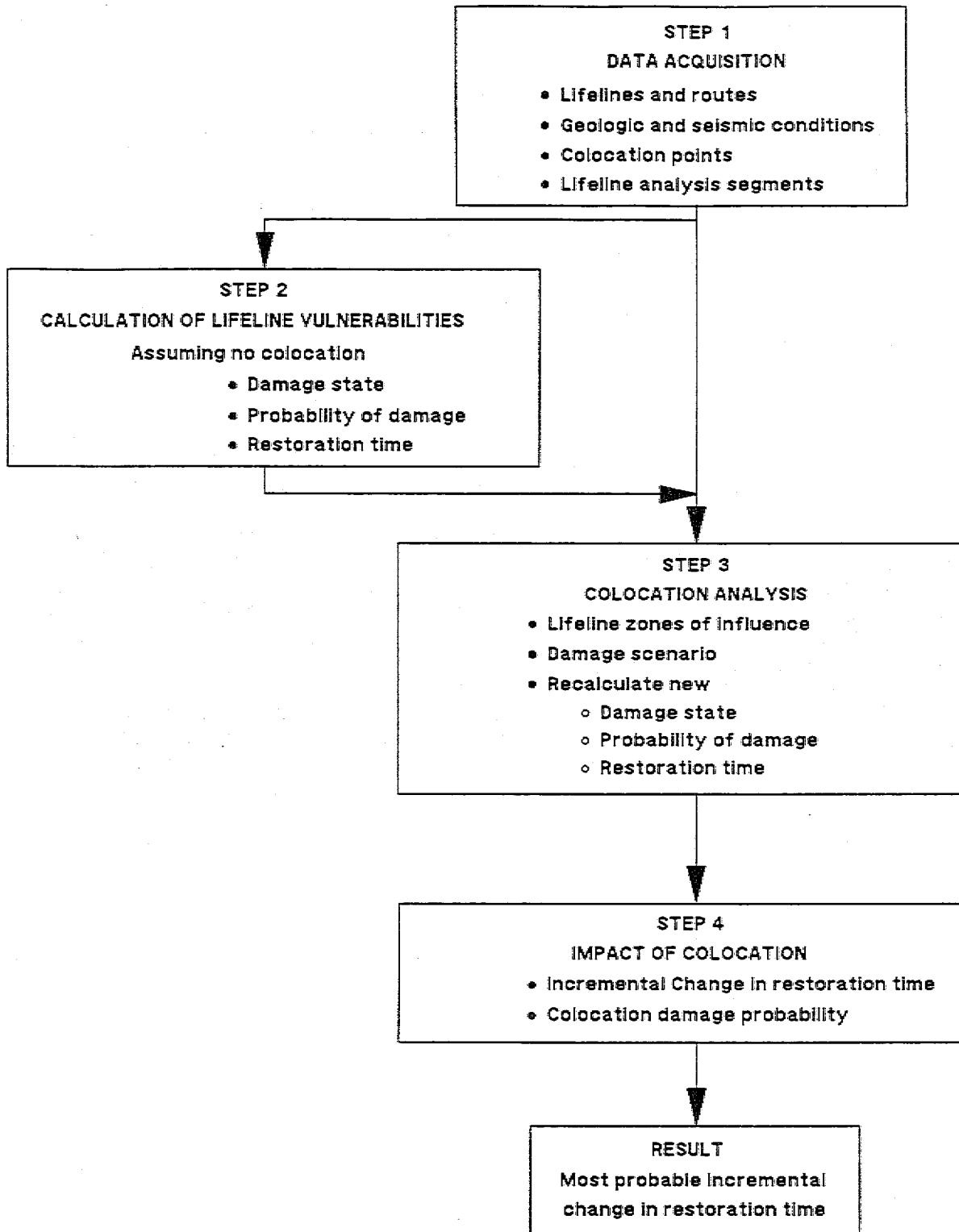   4) Interpretation of the Collocation Impacts.

Briefly, these activities include:

   Data Acquisition

This task is to assemble all of the information that defines the lifelines and their routes as well as the geologic and seismic

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FLOW CHART OF ACTIVITIES FOR CALCULATING COLOCATION-INDUCED LIFELINE VULNERABILITIES DURING EARTHQUAKES

```
                        ┌─────────────────────────────────────┐
                        │              STEP 1                  │
                        │         DATA ACQUISITION             │
                        │                                      │
                        │   • Lifelines and routes             │
                        │   • Geologic and seismic conditions  │
                        │   • Colocation points                │
                        │   • Lifeline analysis segments       │
                        └─────────────────────────────────────┘

┌─────────────────────────────────────┐
│              STEP 2                  │
│  CALCULATION OF LIFELINE VULNERABILITIES │
│                                      │
│        Assuming no colocation        │
│            • Damage state            │
│            • Probability of damage   │
│            • Restoration time        │
└─────────────────────────────────────┘

              ┌─────────────────────────────────────┐
              │              STEP 3                  │
              │         COLOCATION ANALYSIS          │
              │                                      │
              │   • Lifeline zones of influence      │
              │   • Damage scenario                  │
              │   • Recalculate new                  │
              │        o Damage state                │
              │        o Probability of damage       │
              │        o Restoration time            │
              └─────────────────────────────────────┘

              ┌─────────────────────────────────────┐
              │              STEP 4                  │
              │        IMPACT OF COLOCATION          │
              │                                      │
              │   • Incremental Change in restoration time │
              │   • Colocation damage probability    │
              └─────────────────────────────────────┘

                   ┌───────────────────────────┐
                   │           RESULT          │
                   │  Most probable incremental │
                   │  change in restoration time │
                   └───────────────────────────┘
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conditions that will place loads on the lifelines. Some analysis and organization of the resulting information is included in this step to facilitate the application of the analysis method to the specific conditions of interest. Such analyses include identifying the collocation sites as well as dividing the lifelines into consistent sections for subsequent analysis.

Calculation of Lifeline Vulnerability

The geologic conditions identified during the data acquisition are used as input to a seismic analysis. Such data include the topology of the area being studied, a description of the sediment and rock structures, locations of water, and identification of surface ground slopes. Seismic conditions include identifying the location and type of the anticipated earthquake. These are used to estimate the earthquake shaking intensities (it is recommended that Modified Mercalli Intensity (MMI) indices be used to characterize the shaking intensity) and earthquake-induced landslides and soil liquefaction locations.

During this analysis step, the earthquake intensities and ground movements are use to determine the vulnerability of each lifeline at each collocation site as if it were the only lifeline at that site (e.g., as if there were no collocation there). Based on the design and placement of the lifeline component or segment and the seismic loads placed on it, the resulting damage state, probability that the damage state will occur, and the time required to restore the lifeline to its intended service can be calculated. The restoration time is the sum of the time to repair the lifeline assuming all the equipment, material, and repair personnel are available at the damage location, plus the access time required to transport them to the damage location, plus the time required to have them available to transport to the site.

If owner-supplied damage information is not available, it is recommended that the analysis methods, as modified in this report, of "Earthquake Damage Evaluation Data for California", ATC-13, 1985, (prepared by the Applied Technology Council of Redwood City, California) be used. When a study is to be performed for locations outside of California, professional judgement must be applied to determine how to adjust, if at all, the data base of ATC-13. The methods of "Seismic Vulnerability of Lifelines in the Conterminous United State, ATC-25, (presently in print at the Applied Technology Council, and identified as reference 20 in this report section) can be considered for use. However, it is noted that the consistency and validity of the ATC-25 approach has not been examined during the present study, and thus the methods of that study can not be recommended by the Principal Investigators of the present study. It is identified here for information only.

Collocation Analysis

This analysis step builds upon the results obtained from the previous two analysis steps. Based on the actual anticipated damage states for each lifeline at the collocation site as determined in the previous analysis step, a collocation interaction scenario is postulated. The scenario can change either the damage state, the probability that the damage will occur, the restoration time (typically only the access time would be changed and the repair time then would be a new calculation), or any combination of those items. After the individual items are specified, the remaining items (i.e., the non specified damage state, probability, or repair time) are determined using the calculation method applied in the previous analysis step.

Interpretation of the Collocation Impact

This analysis step uses the calculated information of the two previous steps to characterize the impact of lifeline collocation. The most realistic measure of the impact is the "most probable incremental change in the restoration of service time". This is defined as the product of the probability of collocation damage occurring times the incremental increase in restoration of service time (the incremental change in the time to restore service is the restoration time for collocation minus the restoration time with no collocation considered).

Additional details on the recommended analysis approach are provided in Sections 4.1, 4.2, 4.3, and 4.4 below.

4.1 Data Acquisition

Lifeline and Geologic Information

Data acquisition is the first step of any lifeline vulnerability analysis. Information is needed to define the lifelines and their routes as well as to define the geologic and seismic conditions that apply to the lifelines of interest.

Information on the lifelines can be obtained from a number of sources. It is recommended that a site reconnaissance visit be conducted first to help the researchers understand the physical conditions and to preliminarily define the lifelines of interest. In addition, maps from the U.S. Geologic Survey (such as topographic maps published at the quadrangle scale of 1:24,000), state departments of natural resources or mines and geology, the U.S. Forest Service, and highway maps are excellent sources of data. They often indicate lifeline components and routes as well as identify geographic features. The U.S. and state geologic surveys (or departments of mines and geologies, etc.) will also have maps and studies that characterize the earthquake faults, ground units (e.g., the types of sediments and rock formations in

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the areas of interest), landslide locations, water table data, etc.. State offices of emergency response (such as offices of emergency preparedness or seismic safety offices), fire marshal offices, state public utility commissions, water boards and commissions, and the general professional literature on earthquakes are other important sources of information on lifelines and the potential geologic/seismic conditions of interest.

The single most important source for lifeline information is the owner/operators. They will each have detailed route maps and details on their design, construction, and installation. However, as built drawings and construction information are frequently different than the "design" information. Thus, it is important to discuss the information received with the suppliers, and to validate the understanding received with data from other sources and site reconnaissance visits.

Once the applicable lifeline data has been assembled, the lifeline collocation or close proximity locations in the study region should be identified and given a reference number. Also, each lifeline should be divided into convenient segments that are reasonably uniform in their characteristics. These activities are done to aid in the subsequent analysis steps. The application of the analysis algorithms (to be described below) can be separately applied to each lifeline collocation location, using the list of collocation location points as a check that all the needed locations were considered, and using the lifeline segments to identify the physical conditions at the collocation point being analyzed.

The lifeline segments or divisions selected for analysis should be reasonably "uniform" in that the lifeline components should be similar within the segment, the shaking intensity (as measured by the Modified Mercalli Intensity (MMI)) index should be similar, the ground conditions should be similar (that is, areas of ground movement should be analyzed separately from areas of stable ground), and access for repair crews, equipment, and material to the lifeline proximity points along the segment should be reasonably the same. With this approach, lifelines, such as buried pipelines or electrical transmission lines, can be divided into long segments. Their division is primarily set by the ground conditions and the MMI values. Other lifeline systems that have frequent component changes in them, such as transportation systems that include bridges separated by roadbeds, need to be separated by component and access route, and sometimes the roadbed must be further divided to account for ground condition or MMI changes.

Whenever possible, standard measures of earthquake events should be used to characterize the seismic conditions in the study area. In this way the results of the study more readily can be compared with other published data, which allows the conclusions to be validated by such other available information. Thus, earthquake magnitude or the earthquake "size" can be represented by the Richter scale.

Ground Shaking Intensity

Several methods to characterize the intensity of the shaking of an earthquake were considered. Items considered included the magnitude and extent of the shaking. Although ground acceleration, velocity, and displacement are more appropriate for evaluating specific lifeline designs, the use of intensity scales are more dominant in the literature. Rossi-Forell (RF) and Modified Mercalli Intensity (MMI) scales are commonly used as a measure of intensity. MMI is recommended for use since it is more widely used in the earthquake literature, although it is a subjective scale that is dependent on individual interpretation of its meaning. Appendix A presents the detailed definitions of MMI.

The MMI scale includes 12 categories of ground motion intensity from level I (not felt) to level XII (total damage). The use of Roman numerals was done to discourage analysts from trying to consider half scale values. This further implies that the MMI is a broad measure of the shaking intensity. The individual MMI scales are almost exclusively characterized in terms of building damage, so their usefulness for modern lifeline structures and components is somewhat restricted. ATC-13[2] provides a detailed estimate of lifeline damage probability as a function of the MMI scale. As an example of potential interpretation problems, the MMI scale IX identifies that "underground pipes are sometimes broken" while ATC-13 for MMI = IX estimates in California that pipe breaks will occur with a total probability of 91.3%. This illustrates the subjective nature of the MMI scale. Nevertheless, it is commonly used to characterize earthquake intensity, and for consistency it recommended as the proper characterization parameter for examining the collocation impacts on lifeline vulnerability to earthquakes.

Although there are two computer models[3,4,5] that calculate earthquake intensity and that are applicable to the conterminous U.S., the Evernden[3,4] model is recommended because it has been verified by comparison with historical earthquakes, it incorporates the local sediment conditions and such sediment conditions are generally available in the national U.S. Geological Survey geologic data base and in the data bases of the various state offices of mines and geology or natural resources, it is easy to use, it is readily available to researchers, lifeline owners, and to others who may need to apply the methods of this study to other regions in the U.S., and it facilitates comparisons of this research with that of others[7] who have used the Evernden Model. The Advisors to this Project were concerned that the Evernden model may not be as accurate near the earthquake fault location (it appears to underestimate the MMI values there) as it is in predicting the far field effects. Discussions with the staff of the California Division of Mines and Geology confirmed that they had similar concerns. The recommended solution is to increase the calculated MMI value by one scale level at locations near the earthquake fault zone. For most lifeline components this is expected to have a

small impact, because the fault displacement effects there are expected to overshadow the shaking effects represented by the increased MMI value.

The Evernden model has been coded in a computer program, QUAK2NW3. Appropriate input data files are available with the model, and they were verified for use in the present study. They include:

(1) a fault data file that identifies the location of the geologic fault by a series of uniform point sources. They can be spaced as closely as desirable.

(2) a ground condition file that identifies the soil conditions (soil and ground geologic units or descriptions). The spacing of these ground units provides the calculation grid for the program. Evernden typically organizes the ground condition into 0.5 minute latitude by 0.5 minute longitude grids, and they were used for the present study.

(3) a pseudodepth term "C" which is chosen to give the proper near-field die-off of the shaking intensities. Evernden has previously analyzed earthquakes along the San Andreas fault, and his value of C (10 kilometers) was used in this study. Values for other faults can be selected with consultation with Dr. Evernden or by professional judgement.

(4) an attenuation parameter "k" which controls the rate of die-off of peak acceleration as a function of distance from the fault being analyzed. Evernden has identified a value for coastal California, eastern California and the Mountain States, the Gulf and Atlantic Coastal plains, and the rest of the eastern U.S., and these values are shown in Figure 2. The coastal California value was used in this study, k = 1.75.

With the above input, QUAK2NW3 computes the acceleration associated with the energy release along each position of the fault. Earthquake intensities are calculated in terms of the Rossi Forell scale, and then the MMI value is computed from a correlation that Evernden developed for that purpose. The intensity is first computed for a reference ground unit condition (e.g., saturated alluvium), and then the intensity value at each grid point is adjusted for the actual ground condition specified in the ground condition file. The output of QUAK2NW3 can be used as input into a digital plotting program, so that the regions of uniform MMI index can be automatically plotted over the routes of each lifeline system studied. In the present study the commercially available program "AutoCAD" was used, although other similar programs would be just as appropriate. An important criteria for the selection of the plotting program is that it should be able to read the

Figure 2, THE "ATTENUATION PARAMETER k" FOR USE IN CALCULATING
EARTHQUAKE SHAKING INTENSITY
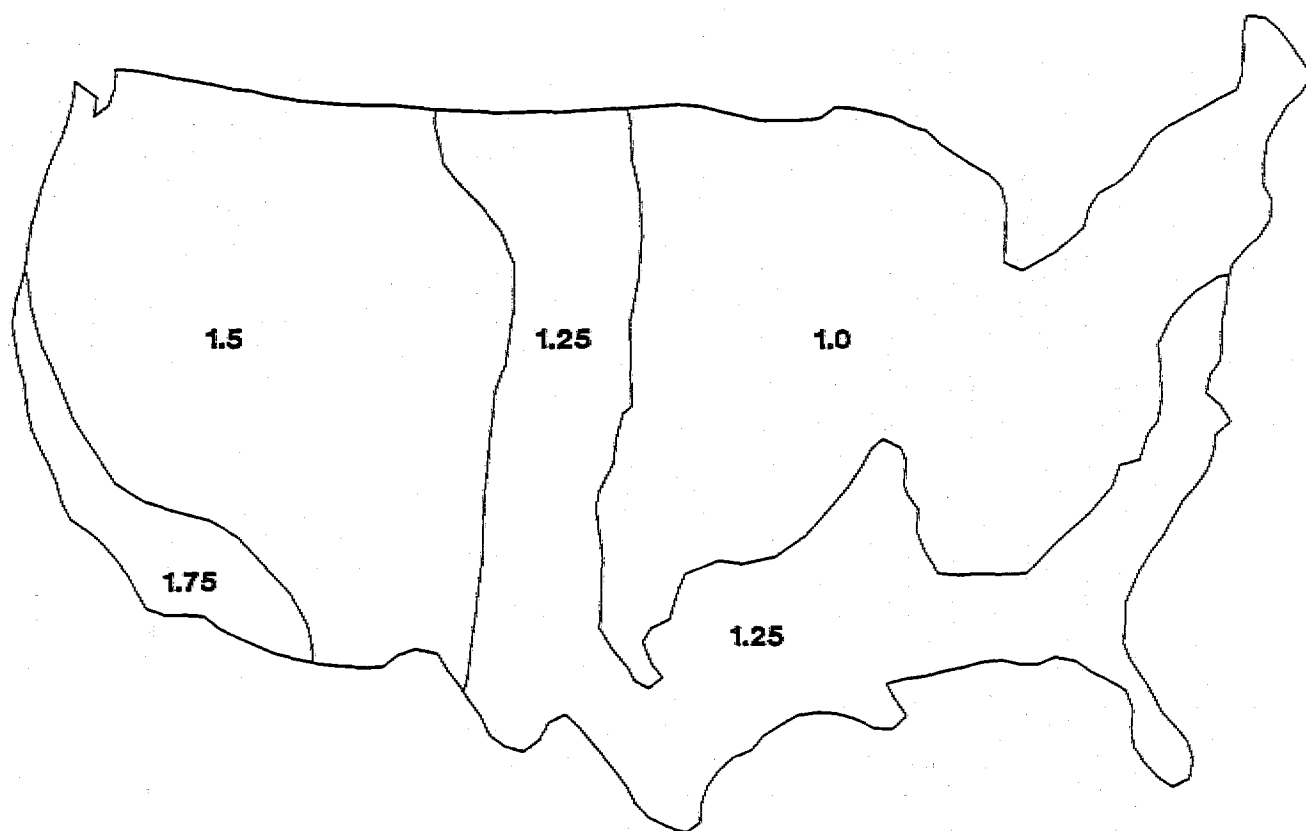
APPROXIMATE PATTERN OF ATTENUATION CHARACTERISTICS (k-VALUE DISTRIBUTION) THROUGHOUT THE CONTERMINOUS UNITED STATES

ditigitized files of the U.S. Geological Survey topographic maps.
Those maps include the routes of many of the lifelines and the
geographic elevation contours. Later when ground slopes are needed
to calculate landslide and liquefaction potential, the computer
program can be used to automatically perform the calculations.
Thus, a single program can conveniently incorporate and graphically
present all the key data: lifeline location, fault traces, MMI
values, and ground slopes.

Selection of the Earthquake Event

The next step is to identify the earthquake event for the analysis.
Based on the faults in or near the study region, the QUAK2NW3
program can be used to perform a sensitivity evaluation to identify
the appropriate earthquake event. All that is required is to input
various earthquake events (length and location of the fault
movement, the ground conditions, the depth of the earthquake, and
the attenuation parameter). The results of several analyses can
then be compared to identify the most realistic event for the
analysis. Key additional data that should be considered is the
prediction of the magnitude and the probability that an earthquake
will occur near or in the study region. Such predictions are
available from Federal and state seismologic offices.

4.2 Calculation of Lifeline Vulnerability

Again, it is recommended that the lifeline owners/operators be
consulted to determine if they already have detailed calculations
on their lifeline's vulnerability to earthquake events. If so,
that approach may be the most detailed available. As an
alternative, the following sections identify how the ATC-13
information, with important modifications, should specifically be
used if such owner/operator information is not available.

Damage Assessment

To determine the potential damage state that occurs, the impacts of
shaking, fault displacement, and soil movement due to either
landslide or liquefaction conditions have to be considered. The
total damage state is the sum of these individual components;
however, if one of these components dominates the others it can be
used without adding the other damage states (this is often the
actual situation). However, when that is done a similar approach
must be used for both the analysis performed while assuming no
collocation impacts and for the analysis performed while assuming
collocation impacts. Also, adding the separate damage states may
over estimate the total damage state. Knowledge of the physical
situation and professional judgement must be applied to determine
the realistic total damage state.

There are seven categories of damage state defined in ATC-13. They
are shown in Table 2.

Table 2
ATC-13 DEFINITION OF LIFELINE DAMAGE STATE

Lifeline Damage State		For Non Pipeline Lifelines	For Pipeline Lifelines	
No.	Description	% Damage	Breaks/kilometer	% Damage
1 -	None	0	0	0
2 -	Slight	0.5	0.25	0.6
3 -	Light	5	0.75	2
4 -	Moderate	20	5.5	14
5 -	Heavy	45	15	38
6 -	Major	80	30	75
7 -	Destroyed	100	40	100

In the present method, the important parameter is the identification of the Damage State Number, a number from 1 to 7. Thus, percent damage or breaks per kilometer are not the needed variable. The experts that developed ATC-13 used the following definitions for damage state: percent damage meant the estimate of the dollar value of the earthquake damage divided by the dollar cost to replace the entire lifeline. However, for pipelines they were asked to think in terms of breaks in a pipeline per kilometer of pipeline length. Within a kilometer segment, 15 breaks may actually cost the same as 40, since the expected procedure would be to simply replace the entire kilometer length rather than to make such a large number of individual repairs and still be concerned that an additional partial break was undiscovered and thus remained unrepaired. Similarly, an electrical transmission tower with 45% physical damage would probably be replaced entirely, as it would not be worth the risk to the owner to make such extensive repairs when a new tower may be less expensive to install and certainly would be more reliable in the future. Thus, when the ATC-13 definition is applied to a large number of similar lifeline components, then, on the average, the damage state may properly predict the condition of the sum of the individual repair costs divided by the total replacement costs for all the components.

However, in the present analysis method, the ATC-13 data will be applied to individual lifeline components. It is acceptable to use the data in this manner as it provides an expert knowledge base for estimating the damage state, and the final result of interest in the present analysis method is not the damage state but a time to restore lifeline service. Its use for single lifeline components would be less accurate if the desired result were the percent damage to be used to calculate a cost of repair (that is, ATC-13 is more accurate for costs averaged over a large number of cases than it would be for a single case). The proposed analysis method could, however, be improved if a new expert opinion study of the damage state and probability for that damage state for single lifeline components were to become available.

The following material indicates how the data of ATC-13 are

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proposed for use in evaluating the collocation impacts of lifelines during earthquake events.

Shaking Damage

The shaking impact of the earthquake event can be estimated by using Table 7.10 (pages 198-217) of ATC-13. For convenience, the more frequently needed tables for lifeline analysis are reproduced in this report as Table 3.

These tables present the collective judgement of the probability that a class of lifeline components will incur a given damage state level, as a function of the Modified Mercalli Intensity (MMI) index. They were developed by using a modified Delphi method that employed a large number of experts who provided their opinion as to what was the probability that a damage level would be experienced for a given imposed value of shaking intensity, MMI.

The trend in the probability data would normally be expected to show that, as the MMI increases, more of the lifeline components would be expected to experience higher damage states. Thus, for increasing values of MMI, the shape of the probability curve should be expected to have its peak value move towards higher damage states and the magnitude of the peak value decrease as the width of the probability curve increases. However, at MMI = XII the probability curve should again focus over the narrow band of damage states 6 and 7. The information for bridges, highways, and buried pipelines and conduits follow this pattern. It is less evident for electrical transmission towers and railroads. The methodology for calculating shaking damage collocation impacts, because it is based on the ATC-13 data, will be less accurate for electrical transmission towers and railroads, compared to buried pipeline and conduits, highways, and bridges. Still, the Principal Investigators and Advisors for this project judged that the data was adequate for the analysis purposes proposed in this report.

In Table 3 the lifeline items are: Facility Class 24-multiple single span bridges; Facility Class 25-continuous/monolithic bridges; Facility Class 31-underground pipelines; Facility Class 47-railroads; Facility Class 48-highways; Facility Class 55-electrical towers less than 100 feet high; and Facility Class 56-electrical towers more than 100 feet high.

In this report the ATC-13 shaking damage data is used in the following manner. For the lifeline component or segment being considered, the appropriate table is entered using the MMI value at the collocation being analyzed. The table is entered to identify the greatest probability value in the column under the MMI listing. In the sample below enter the table (on page 21) for MMI = VIII. Reading to the left of that maximum probability, the most probable damage state is then read from the left most column.

Table 3
SHAKING DAMAGE PROBABILITY MATRICES, ATC-13 Tables 7.10

Damage Probability Matrices Based on Expert Opinion for Earthquake Engineering Facility Classes

Damage
State

Modified Mercalli Intensity

Multiple Single Span Bridges

Damage State	VI	VII	VIII	IX	X	XI	XII
1	3.0	***	***	***	***	***	***
2	97.0	12.3	***	***	***	***	***
3	***	85.7	70.9	***	***	***	***
4	***	***	29.1	71.1	***	***	***
5	***	***	***	28.9	82.4	***	***
6	***	***	***	***	16.9	100.0	***
7	***	***	***	***	***	***	100.0

Continuous/Monolithic Bridges

Damage State	VI	VII	VIII	IX	X	XI	XII
1	93.6	8.1	0.9	***	***	***	***
2	6.4	77.8	17.6	***	***	***	***
3	***	14.1	78.6	56.5	***	***	***
4	***	***	2.9	43.5	1.8	1.2	0.7
5	***	***	***	***	98.2	36.8	5.7
6	***	***	***	***	***	61.9	39.1
7	***	***	***	***	***	0.1	54.5

Underground Pipelines and Conduits

Damage State	VI	VII	VIII	IX	X	XI	XII
1	100.0	99.8	20.9	8.7	***	***	***
2	***	0.2	54.1	34.2	1.3	***	***
3	***	***	17.2	36.1	7.9	0.5	***
4	***	***	7.8	21.9	89.5	66.5	4.5
5	***	***	***	***	1.1	29.6	56.4
6	***	***	***	***	0.2	3.3	37.9
7	***	***	***	***	***	0.1	1.2

***Very small probability

Table 3 (Continued)
SHAKING DAMAGE PROBABILITY MATRICES, ATC-13 Tables 7.10

Damage State — Modified Mercalli Intensity

Railroads

Damage State	VI	VII	VIII	IX	X	XI	XII
1	94.1	9.8	0.1	***	***	***	***
2	5.9	55.4	12.3	0.3	***	***	***
3	***	34.8	87.0	73.9	35.5	10.2	0.4
4	***	***	0.6	25.8	64.1	80.8	25.5
5	***	***	***	***	0.4	9.0	67.9
6	***	***	***	***	***	***	6.2
7	***	***	***	***	***	***	***

Highways

Damage State	VI	VII	VIII	IX	X	XI	XII
1	93.3	18.8	2.8	1.0	***	***	***
2	6.7	61.5	27.0	13.8	1.3	0.1	***
3	***	19.7	68.8	75.4	59.0	20.5	4.6
4	***	***	1.4	9.8	39.1	65.2	50.2
5	***	***	***	***	0.6	14.2	43.4
6	***	***	***	***	***	***	1.8
7	***	***	***	***	***	***	***

Electrical Towers Less Than 100 Feet High

Damage State	VI	VII	VIII	IX	X	XI	XII
1	94.1	6.9	1.0	***	***	***	***
2	5.9	78.8	51.0	2.9	***	***	***
3	***	14.3	48.0	96.3	63.7	10.6	0.5
4	***	***	***	0.8	36.3	82.7	39.0
5	***	***	***	***	***	6.7	59.2
6	***	***	***	***	***	***	1.3
7	***	***	***	***	***	***	***

Electrical Towers More Than 100 Feet High

Damage State	VI	VII	VIII	IX	X	XI	XII
1	93.6	7.3	1.8	***	***	***	***
2	6.4	72.1	50.9	7.5	0.3	***	***
3	***	20.6	47.3	92.2	72.5	16.6	0.8
4	***	***	***	0.3	27.2	79.4	38.2
5	***	***	***	***	***	4.0	58.8
6	***	***	***	***	***	***	2.2
7	***	***	***	***	***	***	***

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***Very small probability

Sample ATC-13 Shaking Damage Matrix

Damage State	Modified Mercalli Intensity Index						
	VI	VII	VIII	IX	X	XI	XII
1	100	99.8	20.9	8.7	-	-	-
2	-	.2	**54.1**	34.7	1.3	-	-
3	-	-	17.2	36.1	7.9	.5	-
4	-	-	7.8	21.9	89.5	66.5	4.5
5	-	-	-	-	1.1	29.6	56.4
6	-	-	-	-	.2	3.3	37.9
7	-	-	-	-	-	.1	1.2

For a MMI = VIII, the largest probability is 54.1 (identified in bold); therefore the assumed damage state is damage state 2 (also in bold). The probability that the damage state or greater will occur is the sum of its probability and all the probabilities for larger damage at the MMI value of interest: (54.1 + 17.2 + 7.8) = 79.1%, or 79% for use in the subsequent analyses.

The data represented in Table 3 was developed based on assuming the facility construction methods were in California. Since California has incorporated seismic design criteria in some of their codes and standards, it raises a question as to how the data should be applied to other U.S. regions. The most direct approach would be to consider the design and construction practices at the study area in question, and to adjust the damage state predicted by Table 3 to account for differences with respect to California.

Rojahn[20] has developed a different approach. He suggests that the MMI value can be adjusted to account for the different design and construction practices. Increasing the MMI value would imply that the local practices are less conservative for earthquake considerations than those used in California. Decreasing the MMI value would imply the opposite. Figure 3 shows the U.S. divided into seismic hazard regions. The Rojahn adjustments for are presented in Table 4. He has used Figure 3 to divide the U.S. into five broad regions: California region 7; Other U.S. areas of region 7; California regions 3 to 6; Puget Sound region 5; and all other U.S. regions.

Table 4 is provided for information purposes. Data for additional lifeline components are provided in reference 20. Rojahn did not justify the selection of the Table 4 values or explain why adjustments are needed for California (recall that ATC-13 was based on assuming that it applied to California). One of the important recommended follow-on studies to the present work is to apply the present screening tool to another U.S. location. One purpose of such a study would be to examine the validity of the adjustments to MMI recommended by Rojahn.

Figure 3, MAP OF U.S. SEISMIC HAZARD REGIONS

NEHRP Seismic Map Areas (ATC, 1978; BSSC, 1988).
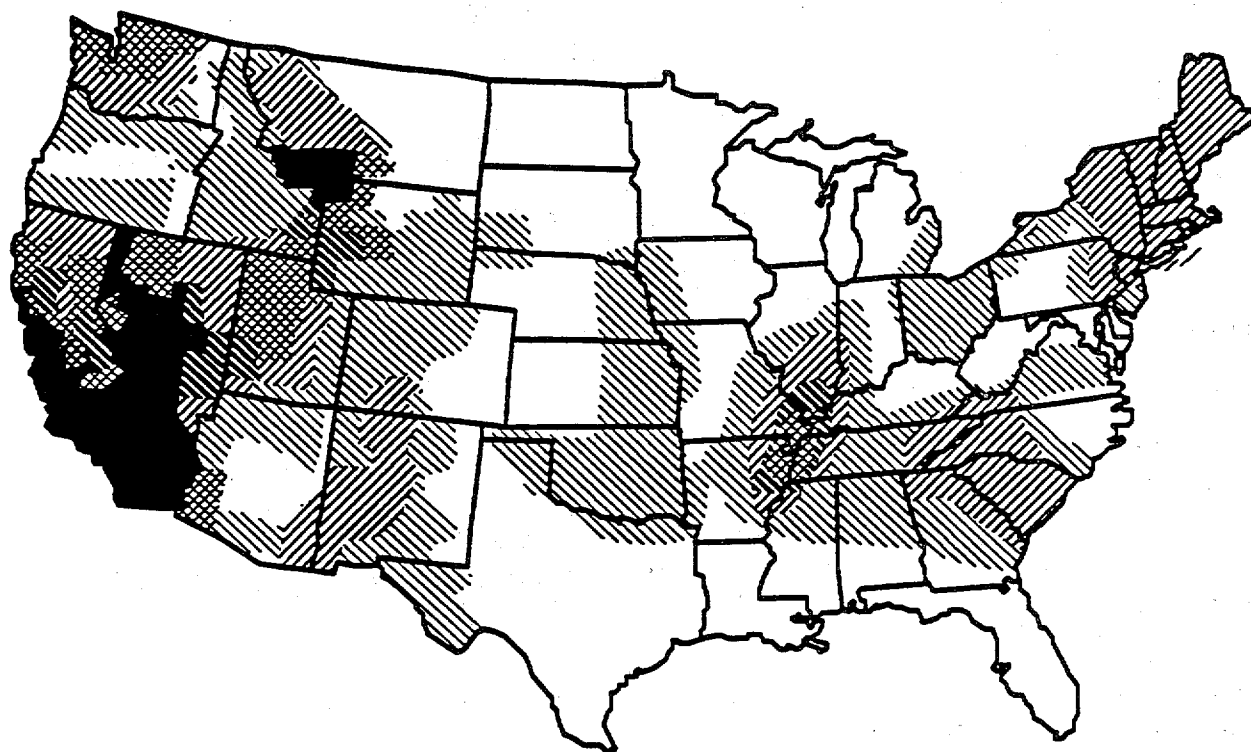
Seismic Risk
Regions

■	7
▨	6
▨	5
▨	4
▨	3
▨	2
□	1

Table 4
MMI ADJUSTMENT FOR SHAKING DAMAGE EVALUATION
TO ACCOUNT FOR LOCAL CONDITIONS
(the region numbers correspond to the numbers of Figure 3)

Region	Multiple Span Bridges	Continuous Bridges	Rail beds & Highways
California, #7	0	0	0
Other area, #7	1	1	0
California, #3-6	1	1	0
Puget Sound, #5	0	1	0
Other U.S. regions	3	2 or 3	0

Region and Number	Railroad Bridges	Water Trunk Lines	Water Pipe Distribution
California, #7	-1	0	1
Other area, #7	0	0	1
California, #3-6	-1	0	1
Puget Sound, #5	0	0	1
Other U.S. regions	1	1	2

Region and Number	Electrical Towers Over 100 ft. high	Electrical Towers Less than 100 ft. high
California, #7	0	0
Other area, #7	0	0
California, #3-6	0	0
Puget Sound, #5	0	0
Other U.S. regions	0	1

Region and Number	Natural Gas Transmission	Natural Gas Distribution	Oil Pipelines
California, #7	-1	0	-1
Other area, #7	-1	0	-1
California, #3-6	-1	0	-1
Puget Sound, #5	-1	1	-1
Other U.S. regions	0	1	-1

Fault Displacement

In ATC-13, the maximum fault surface displacement, D, in meters is calculated from the equation:

$$\text{Log } D = -4.865 + 0.1719 \times M; \text{ where M is the earthquake magnitude}$$

ATC-13 identifies that the fault average displacement is typically 77% of the maximum, and that 30% of the maximum displacement on the main fault is characteristic of the displacement on subsidiary faults.

The damage states for the estimated displacement are obtained from

ATC-13 Table 8.9 and are presented in Table 5.

Table 5
LIFELINE DAMAGE STATE FOR FAULT SURFACE DISPLACEMENTS,
ATC-13 Table 8.9

Facility Type   Damage State (% damage is given in the parentheses)
and Location   For Various Values of Displacement in meters

Displacement =	0.2 m	0.6 m	1 m	3.5 m	10 m
Subsurface Structure					
In Fault Zone	5(50)	6(80)	7(100)	7(100)	7(100)
In Drag Zone	4(20)	5(40)	5(60)	6(80)	7(100)
Surface Structures					
In Fault Zone	3(10)	4(30)	6(70)	7(100)	7(100)
In Drag Zone	0(0)	0(0)	3(2)	3(10)	4(20)

The "Fault Zone" is defined as being within 100 meters of the fault
trace, the "Drag Zone" is defined as being within 100 to 200 meters
of the fault trace. If lifeline components are judged to have
failed because of fault displacement, then the collocation impact
would be only an increase in the time to restore the lifeline to
its needed level of operation (e.g., damage greater than
catastrophic is not meaningful). Such time increases would be
attributed to the construction activity and the need to assure that
construction on one lifeline does not lead to damage on
reconstructed other lifelines.

Soil Movement

Many texts separately define the impacts due to landslides and
lateral spread (or liquefaction). However, they may be thought of
as being part of a continuum of soil movement with the slope of the
topography being a parameter that identifies whether the movement
should be calculated as a landslide or a lateral spread (or
liquefaction). That is the approach proposed in the present
analysis method.

Landslide (landslides occur on slopes greater than 5°)

It is proposed that the historical landslides in the study area be
identified and considered as potential landslide regions when the
collocation evaluation is made. Keefer and Wilson[10] and Sadler
and Morton[11] have identified that landslides are associated with
many historical earthquakes and that shaking is one of the main
triggering agents for landslides. Actual site reconnaissance
visits are recommended as a means to verify the location of
historical landslides for any area being studied. In the present
study, a comparison of the known slides with the geologic unit map
identified that many of the landslides were associated with areas

where Pelona Schist is the bedrock unit. Other researchers are advised to examine the geologic sediments and rocks in the areas where they intend to evaluate collocation and to be sensitive to the location of Pelona Schist.

It is proposed that the method of Legg et. al.[12] be used to identify additional areas where landslides may occur. It is based on the sliding block model proposed by Newmark[13]; Wilson & Keefer[14] have proposed a similar model. However, the Wilson and Keefer model requires using recorded accelerograms or predictions of ground acceleration while the Legg method is related to using MMI. The Legg model is the method used in ATC-13 to define the damage state and probability of damage for landslides. Also, it will be easier to apply the Legg model to other regions in the U.S.. Because of these items, the Legg method was adopted for predicting additional landslide areas.

The Legg method consists of the following basic steps:

Step 1   Solve for the "critical acceleration" of the slope for a given combination of slope angle and soil properties. A formula derived from the stability solution of an infinite slope was used by Legg and also by Wilson and Keefer, and it is provided below.

Step 2   Use the critical acceleration to enter a table of "slope failure state" versus MMI value. The table values identify the potential for the slope to move as a landslide. The tables are provided as Table 8.7 of ATC-13 and are reproduced below as Table 7.

Step 3   The slope state is related to damage state in Table 8.8 of ATC-13, which is presented below as Table 8. However, the ATC-13 Table 8.8 has been extended to more accurately account for buried lifelines, based upon expert opinion obtained during the present study.

The formula for the critical acceleration is given by:

$$a_c/g = c/(\gamma h) + \cos\theta \tan\phi - \sin\theta \; ; \; \text{where}$$

a_c = the critical acceleration, ft/sec^2
g = the gravitational constant, 32.2 ft/sec^2
c = the effective soil cohesion factor, lb/ft^2
γ = the soil density, typically 100 lb/ft^3
h = the thickness of the soil block, typically 10 ft
θ = the slope angle, degrees
ϕ = the angle of friction of the slope material, degrees
Note, this equation applies to dry slopes.

The soil parameters recommended for use are given in Table 6.

Table 6
SOIL PARAMETERS FOR CALCULATING LANDSLIDE POTENTIAL

Geologic Unit	Cohesion, c (pfs)	Shear Strength Parameters Friction Angle, (degree)
Paleozoic Rocks	300	35
Older Cenozoic Rocks	0	35
Older Alluvium	0	30
Young Alluvium at Shallow Ground Water & Pelona Schist	0	20

Wilson and Keefer[14] have also developed an analysis for saturated and dry slopes. They use a 35 degree friction angle for sands, sandstones, and crystalline rocks, and 20 degrees for clayey soils and shales. They present a graph of the critical acceleration as:
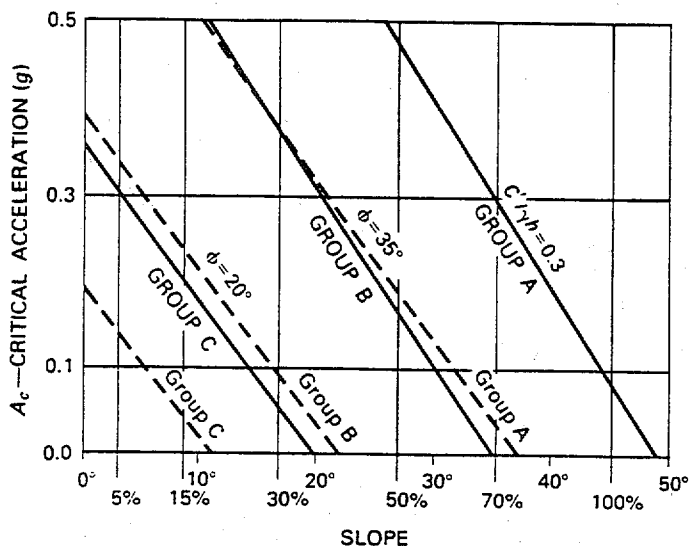
Plots of critical acceleration (A_c) versus slope steepness for three sets of lithologies: group A, strongly cemented rocks (crystalline rock and well-cemented sandstone); group B, weakly cemented rocks (sandy soil and poorly cemented sandstone); group C, argillaceous rocks (clayey soil and shale). The cohesion factor, $c'/\gamma h$, for group A assumes values of $c' = 300$ psf, $\gamma = 100$ pcf, and $h = 10$ ft. The angle of internal friction (ϕ) (peak strength, undrained conditions) is 35° for sands, sandstone, and crystalline rocks and 20° for clayey soils and shales. The solid lines depict dry slope materials, and the dashed lines depict saturation from the slide plane to the surface.

Either the Legg formula or the Wilson graph is acceptable for determining the critical acceleration, it's numeric value will be used in the Legg tables discussed below.

The appropriate soil parameters from Table 6 or other references should be identified. The formula or graph is then used to determine the value of the critical acceleration, which in turn determines the slope stability (unstable, low, moderate, high, stable, very stable) so that the ATC-13 Table 8.7 (Table 7 given below) can be used to define the state of slope failure (Table 7 uses the Legg definitions for terms of slope failure state and slope stability scale, and those definitions also are provided with the table).

Table 7
LANDSLIDE SLOPE FAILURE PROBABILITY MATRICES, ATC-13 Table 8.7

Slope Failure Probability Matrices*
(Summer Conditions)

SLOPE STABILITY: UNSTABLE, $a_c < .01$ g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	0	0	0	0	0	0	0
MODERATE	0	0	0	0	0	0	0
HEAVY	60	50	40	30	20	5	0
SEVERE	30	40	45	50	55	60	50
CATASTROPHIC	10	10	15	20	25	35	50
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: HIGH, 0.3 g $< a_c < 0.5$ g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	95	85	80	60
MODERATE	0	0	0	5	10	15	20
HEAVY	0	0	0	0	5	5	15
SEVERE	0	0	0	0	0	0	5
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: LOW, $.01$ g $< a_c < 0.1$ g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	40	25	15	10	5	0	0
MODERATE	30	30	35	30	20	10	0
HEAVY	25	35	40	40	35	35	30
SEVERE	5	10	10	15	30	35	40
CATASTROPHIC	0	0	0	5	10	20	30
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: STABLE, 0.5 g $< a_c < 0.7$ g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	100	90	85	75
MODERATE	0	0	0	0	10	10	15
HEAVY	0	0	0	0	0	5	10
SEVERE	0	0	0	0	0	0	0
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: MODERATE, 0.1 g $< a_c$ 0.3 g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	85	70	55	20	0
MODERATE	0	0	10	20	25	30	10
HEAVY	0	0	5	10	15	25	40
SEVERE	0	0	0	0	5	15	30
CATASTROPHIC	0	0	0	0	0	10	20
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: VERY STABLE, 0.7 g $< a_c$

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	100	100	90	80
MODERATE	0	0	0	0	0	10	15
HEAVY	0	0	0	0	0	0	5
SEVERE	0	0	0	0	0	0	0
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

Table 7 (Continued)
Definitions

SLOPE FAILURE STATE SCALE

LIGHT-   Insignificant ground
          movement, no apparent
          potential for
          landslide failure,
          ground shaking effect
          only. Predicted
          displacement less
          than 0.5 cm.

MODERATE- Moderate ground
          failure, small cracks
          likely to form,
          cracks similar to
          having a lurch
          phenomena. Predicted
          displacement 0.5 to
          5.0 cm.

HEAVY-   Major ground failure,
          moderate cracks and
          landslide
          displacements with
          effects similar to
          liquefaction or
          lateral spread.
          Predicted
          displacement 5.0 to
          50 cm.

SEVERE-   Extreme ground
          failure, large cracks
          and landslide
          displacements with
          effects similar to
          large-scale fault
          displacement.
          Predicted
          displacement 50 to
          500 cm.

CATASTROPHIC- Total ground
          failure, with
          predicted
          displacement greater
          than 500 cm.

RELATIVE SEISMIC SLOPE
STABILITY SCALE

V -   Very stable, not likely to
      move under severe shaking,
      $a_c \geq 0.7g$.

S -   Stable, may undergo slight
      movement under severe
      shaking, $0.5g \leq a_c < 0.7g$.

H -   High, may undergo moderate
      movement under severe
      shaking, some landslides
      related to steep slopes,
      saturated conditions, and
      adverse dips, $0.3g \leq a_c < 0.5g$.

M -   Moderate, may undergo
      major movement under
      severe shaking or moderate
      movement under moderate
      shaking, numerous
      landslides, rock falls
      abundant, unconsolidated
      material deforms and
      fails, $0.1g \leq a_c < 0.3g$.

L -   Low, may undergo major
      movement under moderate
      shaking, abundant
      landslides of all types,
      $0.01g \leq a_c < 0.1g$.

U -   Unstable, may undergo
      major movement under
      slight shaking, most of
      the area and/or material
      falls, $a_c < 0.01g$.

cm = centimeter
g = gravitational constant

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To use Table 7, it is necessary to enter it with the critical acceleration, a_c, and the MMI value. The critical acceleration value determines which sub-table is used. Within that sub-table, in the MMI column, identify the location with the peak probability. The slope failure state is read from the left-most column at the row that contains the peak probability value. The probability that the condition or worse will exist is the sum of the individual probabilities for that slope state and all worse slope state conditions. This is similar to how the shaking damage state and its probability were calculated.

Next, the slope failure status (light, moderate, heavy, severe, catastrophic) is converted to a damage state (and also a percent damage) by using ATC-13 Table 8.8 (Table 8 below). ATC-13 provides a single conversion value for all lifelines. This has been expanded in Table 8 to account for key buried lifelines. The new values were based on expert opinion obtained during the present study.

Table 8
CONVERSION OF LANDSLIDE SLOPE FAILURE STATE TO DAMAGE STATE
Damage State and (% Damage)

Slope Failure State	ATC-13 Values for all Lifelines	New Values Determine During This Study	
		High Strength Lifelines	Low Strength Lifelines
Light	0-3 (0%)	0-2 (0%)	0-3 (0%)
Moderate	4 (15%)	3 (0%)	4 (30%)
Heavy	5 (50%)	4 (15%)	5 (60%)
Severe	6 (80%)	5 (50%)	6 (90%)
Catastrophic	7 (100%)	7 (100%)	7 (100%)

The definition of high strength buried lifelines used to determine the damage state is: continuous steel pipelines constructed according to modern quality control standards with full penetration girth welds; welds and inspection performed according to API 1104 or equivalent.

The definition of the buried lifelines which should be represented by the original ATC-13 definitions is: pipelines and conduits constructed according to modern standards with average to good workmanship, other than the high strength lifelines defined above. Lifelines in this category are expected to include electric cables, steel pipelines with welded slip joints, ductile iron pipelines, telecommunication conduits, reinforced concrete pipe including concrete steel cylinder pipe, and plastic pipelines and conduits. Also, if the high strength lifelines are oriented so that the landslide motion is expected to place them into compression, they should be analyzed in this category. Other lifelines not included in the High Strength or Low Strength definitions should be

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evaluated using the ATC-13 column.

The definition of low strength buried lifelines is: pipelines and conduits sensitive to ground deformation because of age, brittle materials, corrosion, and potentially weak and defective welds. Lifelines in this category include cast iron, rivetted steel, asbestos cement, and unreinforced concrete pipelines; pipelines with oxyacetylene welds; and pipelines and conduits with corrosion problems. If other non high strength buried lifelines are oriented so that they are perpendicular to the expected landslide motion (e.g., their orientation is such that they will be put into compression by the landslide), then they should be analyzed as a low strength lifeline rather than with the ATC-13 column.

Liquefaction or Lateral Spread (lateral spread occurs on slopes of 1-5°)

It is proposed that the Liquefaction Severity Index (LSI) be used to correlate the liquefaction or lateral spread damage and the probability of damage. The LSI is defined in the work of Youd and Perkins[15]. The following material was developed from expert consultive support provided during this study by Dr. T.D. O'Rourke of Cornell University[6,8,9,16].

In a manner similar to the critical acceleration defined for landslides, a critical LSI is defined in Table 9 below. The basis for its use and the LSI damage probabilities of Table 10 is the work of Harding[6] which has shown that substantial lateral spreading can be triggered at a critical acceleration, a_c, of 0.05 to 0.15 g.

Table 9
RELATIONSHIP BETWEEN LIQUEFACTION SEVERITY INDEX (LSI)
AND DAMAGE STATE

Physical Lateral Ground Movement	Equivalent LSI	Damage State	Damage Condition
< 0.5 inch	< 1	3	light
0.5 to 5.0 inches	1-5	4	moderate
5 to 30 inches	5-30	5	heavy
30 to 90 inches	30-90	6	severe
> 90 inches	> 90	7	catastrophic

O'Rourke has prepared a regression analysis of the observed relationship between the MMI index and the LSI index for four earthquakes; the 1906 San Francisco, the 1964 Alaska, the 1971 San Fernando, and the 1979 Imperial Valley earthquakes. The observations identified LSI values of 5 to 100 for MMI values of V to X. The resulting regression curve (with an $r^2 = 0.68$) is:

$$LSI = 0.226 \times 10^{0.255 \times MMI}$$

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The equation can be used to calculate the LSI number, and then
Table 9 can be used to define the damage state. Graphically, the
relationship between MMI and damage state is presented in Figure 4
below.

The probability that the liquefaction damage state will occur is
given in Table 10. Table 10 (which replaces ATC-13 Table 8.4)
applies to soil environments in which liquefaction is likely to
occur under strong earthquake shaking. These environments include:
active flood plains, deltas, other areas of gently sloping late
Holocene fluvial deposits, and loose sandy fill below the water
table (which are generally placed by end dumping or hydraulic fill
methods). The table does not apply to late Pleistocene Alluvium,
for which the probabilities of liquefaction are negligible for
intensities equal to or less than MMI of X. Thus, the combination
of the LSI equation and Table 9 (or the use of Figure 4) with Table
10 is analogous to landslide calculations for low stability
material.

Table 10
PROBABILITY OF LIQUEFACTION GROUND FAILURE, PERCENT

Liquefaction Damage State	MMI Value						
	VI	VII	VIII	IX	X	XI	XII
3 - Light	75	50	20	10	0	0	0
4 - Moderate	20	30	40	25	15	10	0
5 - Heavy	5	20	30	40	25	25	20
6 - Severe	0	0	10	20	35	40	30
7 - Catastrophic	0	0	0	5	15	25	50

The new method developed during this study adds details to the
level of analysis available from ATC-13. It identifies a range of
damage from light to catastrophic (compared to the assumed
catastrophic levels of ATC-13) and a full range of probabilities
that the damage state will occur. Since it is based on observed
liquefaction damage from California earthquakes, additional
evaluation of the recommended approach at other U.S. locations is
warranted.

Highway and Railroad Bridges

The ATC-13 shaking intensity matrices (Table 3) identify three
broad classes for bridges: multiple simple span bridges, continuous
and multiple span bridges, and long span or major bridges. It is
difficult to fit every railroad and highway bridge into one of
these broad classifications. One example of how owner-supplied
information can be used to improve upon the direct use of the ATC-
13 guidance is found in the methods of the California Department of
Transportation[17,18,19] (CALTRANS). CALTRANS has a method to identify
the priority for performing retrofits to their bridges to reduce
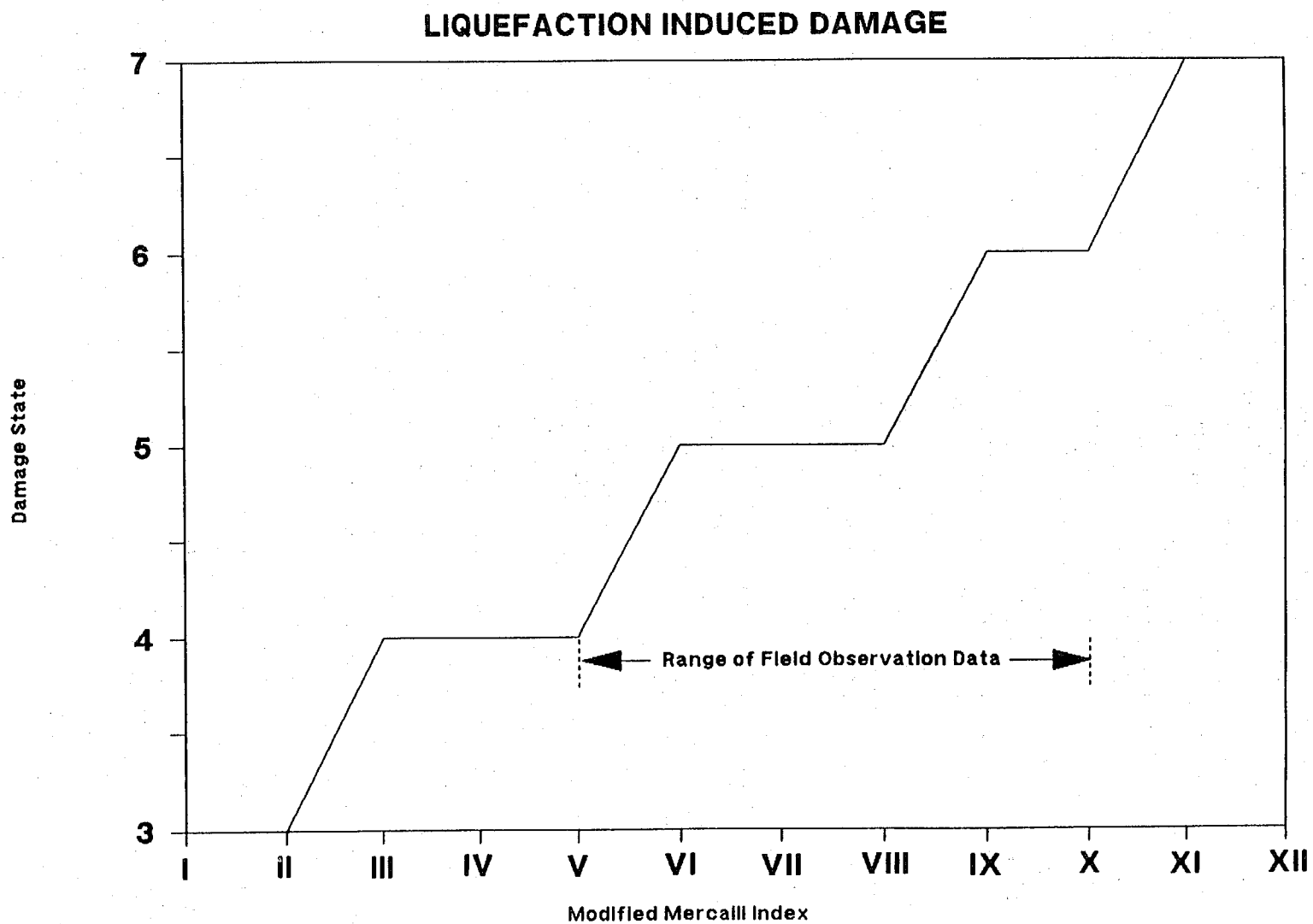their vulnerability to earthquakes. This improved data was

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LIQUEFACTION INDUCED DAMAGE

Damage State (vertical axis)

Modified Mercalli Index (horizontal axis)

Range of Field Observation Data

Figure 4

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integrated with the ATC-13 data to provide more discrimination capabilities for evaluating railroad and highway bridges. The resulting procedures (described below) are fully applicable to locations outside of California if the needed data on the individual bridges are known. The CALTRANS method includes factors, such as traffic loading and detour routes, that are important for making decisions about whether to spend money to retrofit a bridge, but they are not important for determining the damage state of the bridge. However, other factors, such as the bridge sub and superstructure, the design codes used, and the bridge geometry can be related directly to the ability of the bridge to resist earthquake damage.

The method being proposed in this report calculates a parameter that can be used to adjust the damage state value for shaking as determined by the ATC-13 matrices (Table 3 of this report). The evaluation is based on starting with the ATC-13 shaking probability matrix for Continuous and Multiple Span Bridges. The procedures discussed above on how to use Table 3 to define the damage state and the probability that the damage state or greater will occur are used to calculate a tentative damage state. A bridge vulnerability index then is calculated and used to determine if the tentative damage state should be changed (the probability is not changed). The decision to adjust the Table 3 tentative damage state value is based on the numeric values identified below in Table 11 (high values of the Bridge Vulnerability Index mean that the damage will be more severe than that predicted by Table 3).

Table 11
RELATIONSHIP OF BRIDGE VULNERABILITY INDEX TO
BRIDGE DAMAGE STATE

Bridge Vulnerability Index Value	Change to Table 3 Continuous & Multiple Span Bridge Damage State Value
0.0 - 0.2	Lower the Damage State by two increments
0.2 - 0.4	Lower the Damage State by one increment
0.4 - 0.6	No Change
0.6 - 0.8	Increase the Damage State by one increment
0.8 - 1.0	Increase the Damage State by two increments

The numeric value of the Bridge Vulnerability Index is calculated by multiplying a Raw Score by a Multiplying Factor (in the CALTRANS' method, the terms were weighting factor and pre-weighting factor, respectfully). The Raw Score is assigned by the importance of the bridge factor being evaluated, the Multiplying Factor is a weighting scale that determines how earthquake resistant the Raw Score items is. Table 12 presents the numeric values of the Raw Score and the Multiplying Factors.

There are seven categories that are analyzed: 1) abutments; 2) piers; 3) soil type; 4) superstructure type; 5) design code or specification used; 6) bridge height; and 7) bridge skew and curvature. A separate number (the raw score times the multiplying factor) is calculated for each of the seven categories and then the individual numbers are summed. The sum is divided by 100 to give the total Bridge Vulnerability Index value.

In applying the incremental change to a tentative damage state from Table 3, if this results in a damage state less than 1 or greater than 7 use those limit values. Damage states for long span (length greater than 400 feet) and major bridges may be estimated using this procedure, but it is recommended that such structures be subjected to special studies whenever possible. It is emphasized that the above Bridge Vulnerability Index is for shaking damage. Special conditions, such as liquefaction, require additional analysis.

The analysis factors required to enter Table 12 can be obtained from the general design drawings of the bridge or by field reconnaissance. Some assumptions may have to be made with respect to foundation design in the latter case.

Railway bridges have proved to be somewhat more resistant to ground shaking than highway bridges, in spite of the fact that the American Railway Engineering Association (AREA) specifications make no specific recommendations with regard to earthquake forces. This is probably due to the fact that railroad brides have an allowance for lateral loads (originally, the allowance was to account for the loads produced by steam locomotives). Prior to 1935, this allowance was 5% of the live load (typically based on a Cooper E60 engine, or about 852,000 lbs. on a 109 ft. span), but not more than 400 lbs. per foot of track. In 1935, this was changed to provide for a lateral load of 20,000 lbs. applied at the top of the rail at any point in the span. In 1950, AREA provided for higher allowable stresses, so that the allowance became somewhat less conservative. The multiplying factors of Table 12 for railroad bridges reflects these facts.

Table 12
BRIDGE VULNERABILITY INDEX FOR EARTHQUAKE SHAKING DAMAGE

Bridge Element	Raw Score	Multiplying Factor Criteria	Multiplying Factor Value
SUBSTRUCTURE			
Abutments	10	Integral with pile foundation	0.0
		Integral with spread footing	0.5
		Hinge seat with restraints	0.6
		Hinge seat, all other types	1.0
Piers	15	wall	0.2
		multiple column bent	0.5
		single column bent	1.0

Note, if a spread footing foundation is used, add 0.2 to the pier multiplying factor, if the columns have been reinforced to recent seismic codes, subtract 0.3 from the pier multiplying factor.

Soil Type	15	Rock or soil with bearing of more than 4 tons/ft^2	0.0
		Soil with bearing of 2 - 4 tons/ft^2	0.1
		Soil with bearing of less than 2 tons/ft^2	0.5

SUPERSTRUCTURE Type	20	Highway Bridges	
		Simple span, box or slab	0.0
		Single span, arches, reinforced concrete or well constructed masonry	0.1
		Simple span, steel or concrete beams	0.5
		Simple span, steel truss	0.5
		Multiple spans, continuous with no hinges	0.0
		Multiple spans, continuous with 1 hinge	0.5
		Multiple spans, simple beams	1.0
		Multiple spans, continuous with 2 or or more hinges	1.0
		Railroad Bridges	
		Simple spans, steel with full truss	0.3
		Simple spans, deck or half truss	0.4
		Simple spans, steel or concrete ballasted	0.5
		Simple spans, steel or concrete beams	1.0
		Multiple spans, fully continuous	0.0
		Multiple spans, simple beams	1.0
		Multiple spans, continuous with hinges	1.0

Note, for both highway and railroad bridges with hinges, subtract 0.4 from the multiplying factor if restrainers have been added. Subtract an additional 0.3 if the columns have been reinforced to resist earthquake forces.

Table 12 (Continued)
BRIDGE VULNERABILITY INDEX FOR EARTHQUAKE SHAKING DAMAGE

Bridge Element	Raw Score	Multiplying Factor Criteria	Multiplying Factor Value
DESIGN CODE OR SPECIFICATION			
Code used	20	Highways	
		CALTRANS* after 1978 or AASHTO* after 1987	0.0
		CALTRANS between 1972 and 1978	0.2
		CALTRANS prior to 1972 and AASHTO prior to 1950	0.5
		AASHTO from 1950 to 1987	1.0

Note, AASHTO, from 1950 to 1987, leaves the earthquake considerations to the States. If it is known that the State has no such consideration, use 2.0 as the Multiplying Factor value.

		Railroads	
		AREA* from 1935 to 1950	0.5
		AREA from 1950 to present	0.7
		AREA prior to 1935	0.8

Note, for the condition of bridge, modify the design code or specification Multiplying Factor by adding the following to the factor:

		Good or fair condition	0.0
		Poor condition	0.2

Bridge Element	Raw Score	Multiplying Factor Criteria	Multiplying Factor Value
GEOMETRY			
Height	10	Less than 5 feet	0.2
		5 to 15 feet	0.7
		15 to 25 feet	0.9
		25 feet and greater	1.0
Skew* and curvature	10	Skew less than 20° and radius greater than 1000 ft.	0.0
		Skew 20°-40° and/or radius greater than 500 ft.	0.1
		Skew greater than 40° and/or radius less than 500 feet	0.4

Key *
AASHTO, American Association of State Highway & Transportation
        Officials
AREA, American Railroad Engineering Association
CALTRANS, California Department of Transportation
Skew is defined as the angle that abutments and piers make with
respect to the normal to the highway (or railway) alignment.
That is, when the plane of the abutment or pier is aligned
parallel to the normal to the road (or rail bed) alignment, the
skew is 0°.

Times to Restore the Lifeline to its Needed Service

Once the lifeline components of interest have been identified and the damage state and probability that the damage condition or worse will occur have been calculated from the above tables and formulas, the time to restore the lifeline component or segment from the total calculated damage state to the operating level needed has to be determined.

The restoration time is a combination of the time to repair the lifeline segment or component assuming all the equipment, material, and personnel are available at the damage site, plus the access time to get the equipment and material to the damage site, plus the delay time needed to obtain the equipment and material required for making the repair. The way to calculate these items is given next.

Repair Time to restore the damaged lifeline to service

With the damage state known, the time to repair the lifeline component or segment (assuming the equipment and material are at the damage location) can be calculated from Table 9.11 of ATC-13. The key information of Table 9.11 is provided below as Table 13. If intermediate operating conditions (e.g., repair to less than 100% capacity) are acceptable, the intermediate repair times of the ATC-13 tables can be used or the plots of those tables provided by Rojahn[20] can be used to estimate such intermediate condition repair times. The newer curves by Rojahn are curve fits of the data of ATC-13[2], thus they are not exact replications of the data. But they may be more convenient to use since they relate the repair time to MMI instead of to the damage state as is done in ATC-13. Also, if there is concern about the magnitude of the repair time estimated, Table I.1 of Appendix I of ATC-13 can be used to determine the range of repair times identified by the experts that prepared Table 9.11. It is important to recognize that the actual repair time is not used directly to estimate the impact of collocation on the vulnerability of lifelines to earthquakes (as will be shown below).

Eleven of the more important repair tables are presented in Table 13 (some of the tables were adjusted from the ATC-13 values to account for expert opinion obtained during the present study). To make a specific estimate of lifeline repair time, enter the proper lifeline table at the row that identifies the damage state and move to the right until the correct lifeline column is encountered. Then read the time, in days, required to restore the lifeline to full capacity from that damage state. The ATC-13 lifelines of interest are: 18c-petroleum transmission pipelines, 25a-highway major bridges, 25c-highway conventional bridges, 25d-freeways and highways, 26a-railroad bridges, 26c-railroad roadbeds, 29b-electrical transmission towers, 30f-water trunk lines, 31a-sewer lines, 32a-natural gas transmission lines, and 32d-natural gas distribution lines. It should be recalled, however, that better

estimates of repair time are probably available from the individual lifeline owners, as they may have site specific conditions included in their estimates.

Table 13
ESTIMATED LIFELINE REPAIR TIMES TO 100% OPERATING CAPACITY
ATC-13 Table 9.11
(Times in Days)

Damage State	Highway Bed	Railroad Bed**	Highway** Conventional Bridge	Highway Major Bridge	Railroad Bridge	Water Trunk Line
1*	1	1	1	1	1	1
2	1	1	1	2	1	2
3	7	2	8	7	8	3
4	41	11	84	141	58	10
5	147	41	303	392	213	25
6	292	82	686	845	468	74
7	437	120	752	947	606	156

Damage State	Natural Gas** Distribution & Petroleum Lines	Natural Gas Transmission Pipelines	Fiber Optic** Conduits	Electrical Transmission Towers	Sewer Lines
1*	1	1	1	1	1
2	1	1	1	1	3
3	3	3	1	2	5
4	6	11	3	17	18
5	19	25	10	49	63
6	44	44	24	82	102
7	55	75	30	127	141

* Damage State 1 has a 1 day allowance to allow for inspection to determine the actual damage state that exists at the lifeline

** These values were determined by expert opinion during this study

Access Time to get the equipment and material to the damage site

Next it is necessary to estimate the time to get the equipment and repair material to the site. This time is the time to get construction equipment and material to the damage site, and it should not be confused with the time it would take to get general population traffic to the site or with the time it would take for repair crews to get to the damage site. In many situations, and especially for lifelines such as pipelines, fiber optics, and electrical transmission towers, most of the necessary equipment and material can be driven to the damage location either along the highways, unpaved access roads, or cross country if the land is dry

and accessible. In some of the more rugged regions they can be helicoptered to the site. An exception would be if wet ground or large water bodies must be negotiated. Thus, in general, for those lifelines the access time is one or two days, depending upon the location of the segment or component of the lifeline system being examined. If access along the highway is required it should be calculated as described below for the railroads and the highways.

For many of the railroad or highway components and segments, the access will have to be along the railroad or highway itself because of the size and weight of the material and equipment that is required. In such cases, it will be necessary to estimate the repair times for damage along the route prior to the location being studied. The individual repair times must then be added for each disruption that occurs before the location being studied to obtain a total estimated access time. Alternatively, detours can be used to calculate a "by pass" time estimate.

Equipment and Material Time to have those items available

For many of the lifelines, the owners have their own operating equipment and have prepositioned repair material along their lifeline routes. When they don't have suitable repair equipment in their operating stock, they may have existing agreements with other firms to provide such equipment during emergencies. Frequently, utility lifeline owners have reciprocal agreements with other utilities to provide personnel and equipment during emergency periods. This preplanning can decrease the time it takes to have equipment and repair material available to transport to the damage location.

The problem of material availability can be pronounced for railway and highway bridge repairs. In those cases, the time required to fabricate off site the needed components must be accounted for in the estimation of the delays in having equipment and material available.

In almost all cases, it can be assumed that the equipment will not be available during the emergency phase of the earthquake, since it will be diverted to life-saving duty at that time. However, prior earthquake response experience indicates that most equipment and needed material will be made available within one or two days.

4.3 Collocation Analysis

Section 4.2 presented a number of analysis methods that can be used to determine the damage state, the probability that the damage state or worse will occur, and the estimated restoration time to return each lifeline component or segment to its needed service level.

In the collocation analysis activities, a collocation damage

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scenario is developed and the unknown conditions (either damage state, probability of damage, restoration time, or any combination of those items) are recalculated for the assumed collocation damage scenario using the methods of Section 4.2. The collocation damage scenario should be based on the knowledge of how the individual lifelines would have responded if they had be the only lifeline at the collocation point, the estimate of the types of impacts that one lifeline failure could impose on another nearby lifeline, and the zone of influence that one lifeline has.

This process requires that technical judgements be applied, based on knowing the expected damage states of the collocated lifelines, the seismic and geologic conditions, information about the lifelines themselves (such information as the design conditions, construction history, repair and maintenance history, and other pertinent facts), and other lessons learned from prior earthquakes. It will be important to obtain as much information from the lifeline owners as possible to help guide the collocation damage scenario analyses.

It is also important to recognize that there is a zone of influence, beyond which the impact of one lifeline on another would be negligible. During this study, expert opinion was used to estimate the appropriate radii of influence zones for the lifelines found in the Cajon Pass. The results are given in Table 14.

Care must be taken to differentiate between the zone of influence and the actual influence or damage caused. For example, the zone of influence of a failed dam is based on the path of the water that spills past the dam. It includes the actual pathway and the area that the water would inundate. The actual impact of the failed dam could be erosion of foundations of other lifelines (thereby causing them to collapse) or the flooding of them (perhaps restricting their ability to function). There may be no influence on one lifeline, while the impact on another could be pronounced. Some of the impacts may be subtle. For example, a failed communication lifeline may have no immediate impact on the physical state or condition of other nearby lifelines. Its impact, however, could be tied to increasing the restoration time of nearby lifelines due to the difficulty of maintaining communications with the repair personnel. In the present context of lifeline vulnerability, the impact of one lifeline on a collocated or nearby lifeline can be the damage state, the probability of damage, or the restoration of service time. Other impacts, although real, have no way to be accounted for in the analysis method.

Although the values in Table 14 are considered appropriate for the semi-desert region of the Cajon Pass, California, for which they were prepared, it will be important to validate these values when the lifeline zones of influence are evaluated for other at-risk or collocation conditions.

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Table 14
LIFELINE ZONES OF PHYSICAL INFLUENCE

Liquid Fuel Pipeline – The drainage path and catchment area for any liquids spilled; two times the pipe burial depth for any soil cratering impacts due to pipeline ruptures; 100 feet if explosion impacts are estimated; ground erosion paths for liquids spilled; and the burn path if fires are estimated.

Natural Gas Pipeline – Two times the burial depth for any soil cratering impacts due to pipeline ruptures; 100 feet if explosion impacts are estimated; and the burn path if fires are estimated.

Fiber Optic Cables – Zero feet (e.g., no physical impact on other lifelines).

Roadways – 40 feet from the road edge; a possible ignition source for fuel lifelines.

Railroads – 40 feet from the track edge; a possible ignition source for fuel lifelines.

Overhead Electrical – A radius equal to the height of the tower for physical contact; a possible source of ignition for fuel lifelines.
Transmission Towers &
Power Lines

Bridges – For an area centered on the bridge, twice the length of the bridge and 40 feet on either side of the bridge.

Dams, Reservoirs & – The drainage path and inundation areas for the spilled water.
Canals

Water & Sewer Lines – The erosion area downstream of the break (sewers only if they are pressurized); the catchment area for the spilled fluids.

It is anticipated, but not required, that collocation impact scenarios will follow the following general guidance.

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Impacts on Damage State

One of the easier direct impacts to hypothesize will be that the collocation conditions will lead to an increase in the damage state of one or both of the collocated lifelines (if there are more than two collocated lifelines this applies to all of them). It is easy to understand the damage state, as it relates to a physical condition. Because the individual lifeline damage states assuming no collocation are known, those values can be used to help understand how the lifeline could impact another nearby lifeline. If, for example, light damage of a pipeline had been calculated, it would be expected to cause no direct change in the damage state of a nearby bridge. However, if the bridge had been estimated to collapse, it would be reasonable to estimate that within the bridge's zone of influence it would lead to failure of the pipeline (this example also illustrates that the impacts are not necessarily reciprocal).

As another example of how collocation impacts on damage state can be estimated, consider the condition of a pipeline and a fiber optic conduit hung from a bridge. The earthquake vibration may not be enough to cause serious damage to the bridge or to the pipeline or conduit if they were not collocated with each other. However, the vibrations may cause the anchors holding the heavy pipeline to the bridge to fail. As the pipeline sags (but does not fail) it could fall onto the lower conduit, causing it to fail. The collocation damage state hypothesis would then be: no impact on the bridge; a small increase in damage state of the pipeline to account for the work required to rehang the pipeline; and catastrophic failure of the fiber optic conduit.

Special attention should be given to the collocation of fuel carrying lifelines with other lifelines that have the ability to provide an ignition source. The resulting fire and/or explosion could lead to significant collocation damage. Similarly, broken pipelines which eject fluids could lead to foundation erosion problems that would result in increased damage to nearby lifelines.

Impacts on Probability of Damage

The probability of damage does not directly enter into the calculation of the damage state level or the time to repair the damage. It is, as will be discussed below, a very important item for determining the key result of the collocation analysis, the probable incremental change in restoration of service time.

There are several ways to estimate the change in the probability that damage will occur, none are exact and there are no statistics available from the literature on earthquakes. However, there are some insights available to guide the analysts.

If the probabilities for two lifelines, assuming no collocation

conditions, are P1 and P2, they represent an upper bound on the probability that a collocation damage would occur. For example, if the probability that lifeline 1 would fail is P1, and it is known that if lifeline 1 fails it will cause, with a 100% probability, damage to lifeline 2, then the probability that lifeline 2 receives collocation damage is also P1 (e.g., P1 x 100%). Similarly, the upper bound on the probability that lifeline 2 has damaged lifeline 1 is P2.

As a practical matter, the collocation damage likely will be less, since there is seldom a 100% chance that the collocation damage scenario will occur. A useful measure of the probability that the collocation event has occurred is the product of the two probabilities that the single independent events that were used to develop the collocation scenario have occurred (the independent events are the estimate of the damage state of each lifeline assuming there was no collocation). In the present case, that is found by multiplying P1 x P2. The product can be interpreted as follows. It represents the increase in probability that the two independent lifeline damages will occur during the same initiating event. If both events must occur before the collocation damage scenario can take place, then it is a measure of the probability of the collocation damage scenario.

The actual probability that the collocation event will occur should be a number between the numerical limits of P1 and (P1 x P2) for having lifeline 1 cause additional damage to lifeline 2, and P2 and (P2 x P1) for having lifeline 2 cause additional damage to lifeline 1. It is recommended that for calculational purposes, the product P1 x P2 be used to characterize the hypothesized collocation damage scenario.

Impacts on Time to Restore Lifeline Service

As discussed above, the time to restore lifeline service is composed of the sum of the time to repair the lifeline damage, the time to access the damage site with equipment and material, and the time to obtain the equipment and material.

The hypothesized collocation damage scenario does not have to assume a repair time. Once the collocation damage state is known, the repair time can be obtained from Table 13.

However, it is reasonable to include in the collocation damage scenario impacts on accessibility to the damage site, which has the impact of increasing the overall restoration of service time estimate. In fact, this is probably one of the more significant aspects of the collocation damage scenario, e.g., the estimation of the additional direct delays that will be incurred because of the collocation of the lifelines. The greater the level of damage estimated for each of the separate lifelines, assuming that there is no collocation, the greater the anticipated delays that will

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result from their actually being collocated.

The following are offered as possible examples of how collocation could create access delays that would increase the time to restore the lifeline to service. General congestion at the collocation location because there are multiple lifelines could delay the start of repair work on a lifeline. Concern over the possibility of leaking fuel may cause all work to be delayed until it can be confirmed that it is safe to have workers in the area. Spilled liquid fuels may have to be treated and/or removed before construction vehicles and welding (which could provide an ignition source for fuel vapors) would be allowed.

Work on a pipeline buried next to a railroad may be delayed while debris about and on the railroad is removed by heavy equipment. Then, because of the weight of the debris and/or the heavy equipment, the entire pipeline may have to be exposed and inspected before it is allowed to return to service. Often, power transmission towers are replaced with temporary towers while repair work on the damaged tower is performed. However, the use of a temporary tower may limit the access of pipeline and transportation lifeline repair crews because of the increased potential for electrocution if heavy equipment is operated near the temporary tower. Fires at collocation locations can increase the time required to inspect the nearby lifelines to determine the extent, if any, of damage caused by the fire. Water inundation can cause delays until the water is drained and the surrounding ground dries to a condition that allows the repair equipment and material to be delivered to the damage site. Major damage to a lifeline may result in a regulatory review about the suitability of rebuilding (or repairing) the lifeline. While the regulatory review is underway the repair on the lifeline may be delayed.

In summary, a collocation damage scenario must be developed, based on the knowledge of the lifelines and their anticipated damage state if they had been isolated or non-collocated. This will result in the estimation of a new damage state, new access times, or combinations of those items. With the damage state known, a new repair time is calculated, and the repair time and access time are used to determine the new time to restore service.

4.4 Interpretation of the Results

This is the activity that brings together all of the previous analyses.

The most appropriate measure of the impact of lifeline collocation because of an earthquake was judged to be the most probable incremental increase in the time to restore the lifeline to its needed service level. The restoration of service time is a broad measure of the impact of lifeline damage on personnel, equipment, and material resources, it does not measure the impact that the

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loss of the lifeline has on the community that was relying upon it. The difference between the restoration of service time assuming collocation impacts and the shorter restoration time found by assuming no collocation impacts gives the incremental impact that collocation has caused to service restoration. The incremental time impact is a better measure of collocation impacts as compared to the estimated total time to restore service, because any biases in the estimation procedures tend to be canceled by the subtraction process.

It is important to multiply the incremental change in restoration time by the probability that the collocation damage has occurred. This recognizes the uncertainties in the data base and analysis methods provided in Section 4.2, and it also recognizes that in actual earthquakes there is a real probability that a given level of damage will occur, or conversely, will not occur. The product, incremental change in restoration time multiplied by probability, identifies the most probable incremental change in restoration time.

There are two ways to use the final measure:

1) the most probable incremental change in restoration time can be considered at a specific collocation site to evaluate the impacts at that site. This will provide an insight on the vulnerabilities that occur when specific types of lifelines are collocated at at-risk locations. That is, this type of information will help identify which lifeline types or which lifeline design or construction practices, when collocated with other lifelines, lead to the greatest increases to the other lifelines' level of vulnerability.

2) the most probable incremental change in restoration time can be summed along the route of a given lifeline to provide an insight on the impacts that the specific lifeline route has had on the vulnerability of the lifeline. This type of information can be used to help identify undesirable routing decisions.

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